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"Mid-Infrared Fiber Laser Based on Super-Continuum."

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Contractor: Omni Sciences Inc
Principle Investigator: Michael J. Freeman
Business Address: 647 Spring Valley Drive Ann Arbor, MI 48105-1060
Phone Number: (734) 420-0190

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PROJECT FINAL REPORT 1/31/07

The overall goal of the Phase I Supplement was to improve the performance of the bench-top, mid-infrared fiber laser system that had been developed under the Phase I program.

The program succeeded in demonstrating an all-fiber integrated Mid-InfraRed FIber Laser (MIRFIL), see Figure 1, with no optical bench, such that bulk optics are no longer required. More specifically, the all-fiber integrated MIRFIL breadboard generates super-continuum (SC) with 1.2W time-averaged power extending to ~3.4 microns in 60m of ZBLAN fiber. The long wavelength edge of the SC is limited by the bend-induced loss of the particular ZBLAN fiber used in the experiments. The power levels and repetition have been optimized to generate high time-averaged power along with the broadest spectrum supported by the fiber. In addition, the results from the all-fiber integrated MIRFIL are compared with results obtained using the same ZBLAN fiber in a bulk-optical, tabletop, set-up in Prof. Almantas Galvaunaskas's lab, and the results lay almost directly on top of each other. In order to broaden the spectrum out to ~4.6 microns, new ZBLAN fibers with less bend-induced loss will be required, and we are working with fiber makers to fabricate this fiber while maintaining a high damage threshold.

One of the first tasks was to implement and characterize the first stage pre-amplifier. The pulse repetition rate in the pre-amplifier can be varied from 20kHz to 500kHz, and the power is scaled up by increasing the repetition rate.

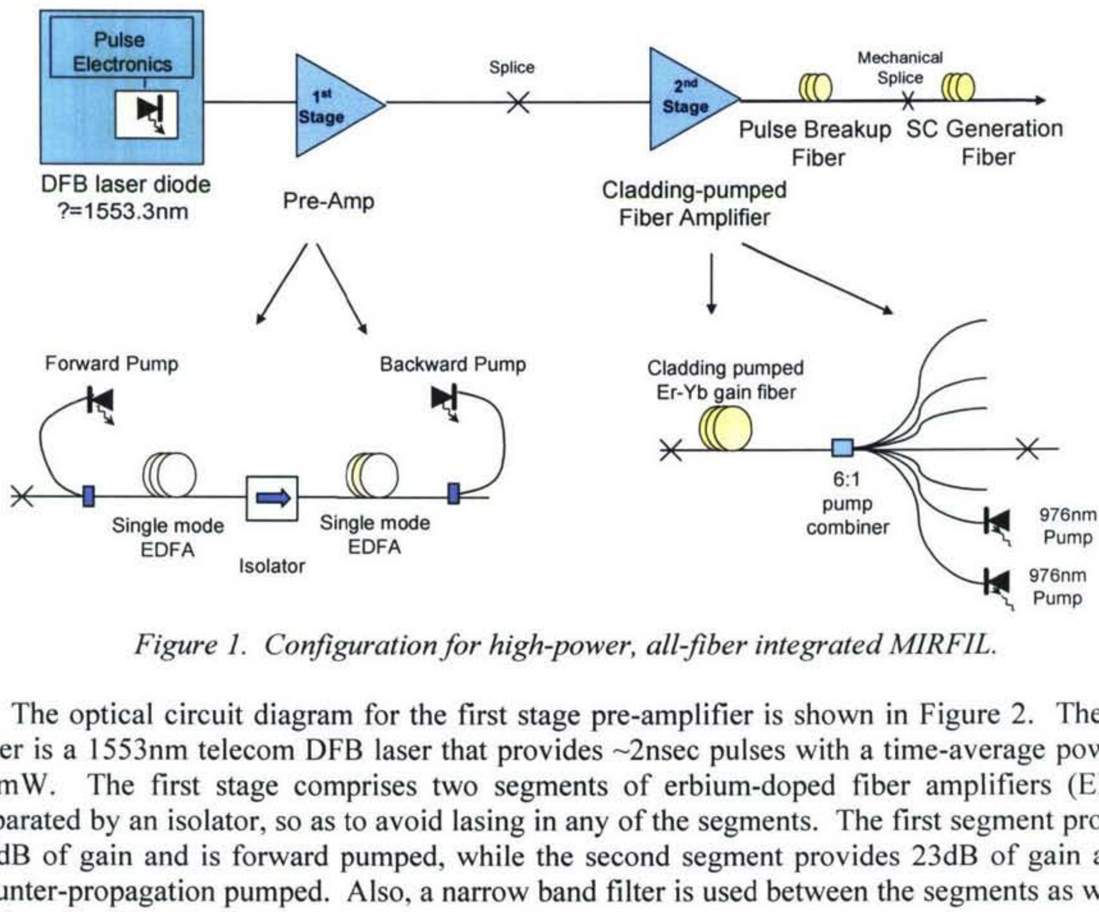

Figure 1. Configuration for high-power, all-fiber integrated MIRFIL.

The optical circuit diagram for the first stage pre-amplifier is shown in Figure 2. The seed laser is a 1553nm telecom DFB laser that provides ~2nsec pulses with a time-average power of 20mW. The first stage comprises two segments of erbium-doped fiber amplifiers (EDFA) separated by an isolator, so as to avoid lasing in any of the segments. The first segment provides 17dB of gain and is forward pumped, while the second segment provides 23dB of gain and is counter-propagation pumped. Also, a narrow band filter is used between the segments as well as at the end of the stage.

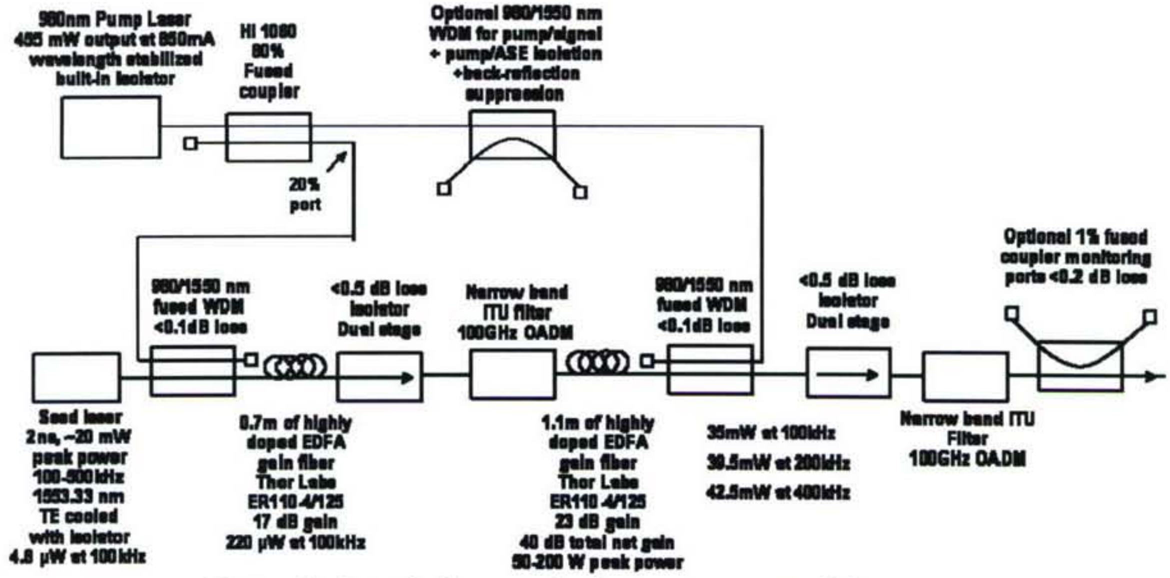

Figure 2. Detailed lay-out for low-noise pre-amplifier.

Next, we focused on improving the 100 mW power amplifier stage, shown in Figure 3. For the 100mW unit, all of the fibers are nearly single spatial mode, at least at the pump wavelength. The gain fiber comprises 1.1m of highly doped, large mode area (LMA) erbium-doped fiber amplifier (EDFA). Two 1480nm pump laser diodes are polarization multiplexed to form over 500mW of pump power, and each of the laser diodes are wavelength stabilized. The pumping is counter-propagating to the signal, thereby minimizing nonlinear effects in the fiber amplifier. A tap is also used to monitor the amplifier performance, while two WDMs are used to insert the pump light and remove any residual pump at the gain fiber entrance.

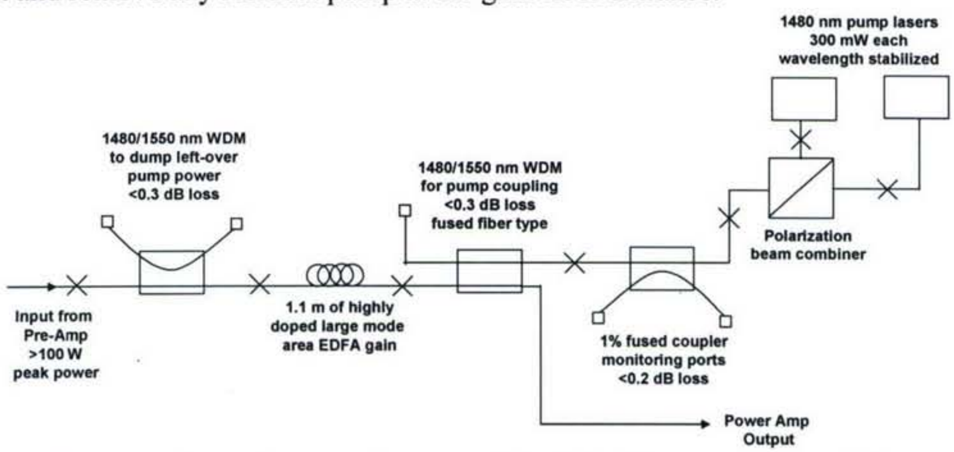

Figure 3. Optical circuit diagram of the 100mW unit power amplifier.

Testing of the 100mW pump unit showed that the pump for the super-continuum can be achieved without using a modulator to reduce the amplified stimulation emission. In addition, the LMA EDFA can be incorporated and spliced into the pump laser set-up, and up to several kilowatts of peak power can be achieved before the onset of super-continuum directly out of the amplifier.

Once the 100 mW pump unit was demonstrated, work shifted to the 1W pump unit. The pre-amplifier stage is split into two sections to avoid the build up of amplified spontaneous emission. By optimizing the design of the pre-amplifier, a temporal modulator is no longer required. The second stage, which is the power amplifier stage, uses a cladding pumped fiber amplifier, see Figure 4. The cladding-pumped, erbium-ytterbium doped fiber amplifier is counter-propagation pumped by two multi-mode laser diodes. The laser diodes operate at ~976nm and output 6W each. The output from the power amplifier is ~3W at a 300-500kHz repetition rate, so the power amplifier has approximately 25% efficiency (common for Er-Yr co-doped systems). At a later date, the power will be scaled up by adding additional laser diodes (currently, a 6x1 coupler is used).

Performance of the power amplifier stage was further improved by appropriate selection of cladding-pumped fiber amplifier (CPFA). In particular, CPFA samples were obtained from CorActive, NuFern and OFS Fitel. The OFS and NuFern gain fibers were found to provide comparable performance, and the following results were obtained using the NuFern gain fiber.

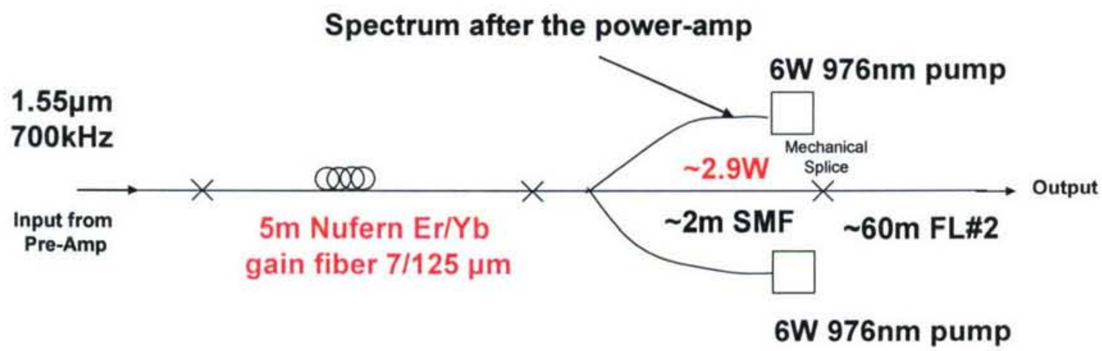

Figure 4. Detailed lay-out for power amplifier stage using cladding-pumped fiber amplifiers.

Using the all-fiber integrated pump system, SC generation was tested using 60m length of ZBLAN FL#2, which is a fiber that has been previously tested using the table-top system in Prof. Galvaunaskas's lab. Figure 5 illustrates the SC generated with a time-averaged power of ~1.2W in the SC and the pump system adjusted to a 700kHz repetition rate. To verify that the all-fiber integrated system is giving similar performance as the table top system, the SC spectra obtained in the two systems using the same fiber is shown in Figure 6. The comparison shows that nearly identical spectra are obtained in the two systems, so the all-fiber integrated MIRFIL has not introduced any new artifacts beyond the table top system.

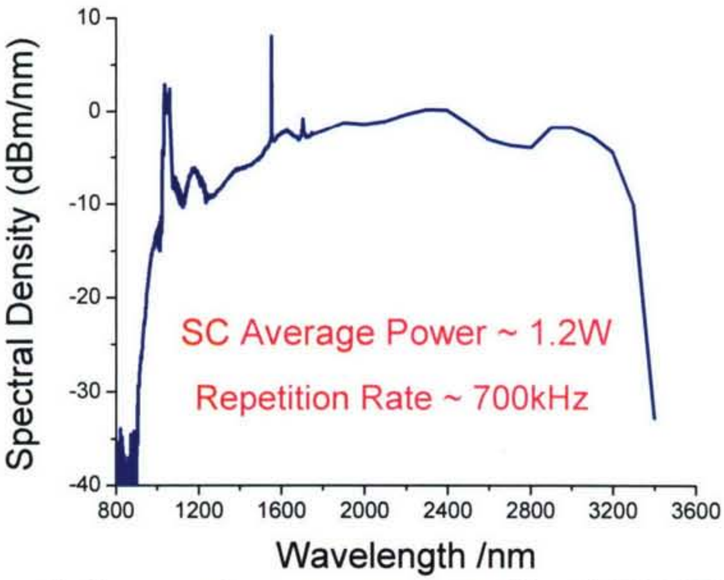

Figure 5. Super-continuum spectrum using 60m of ZBLAN FL#2.

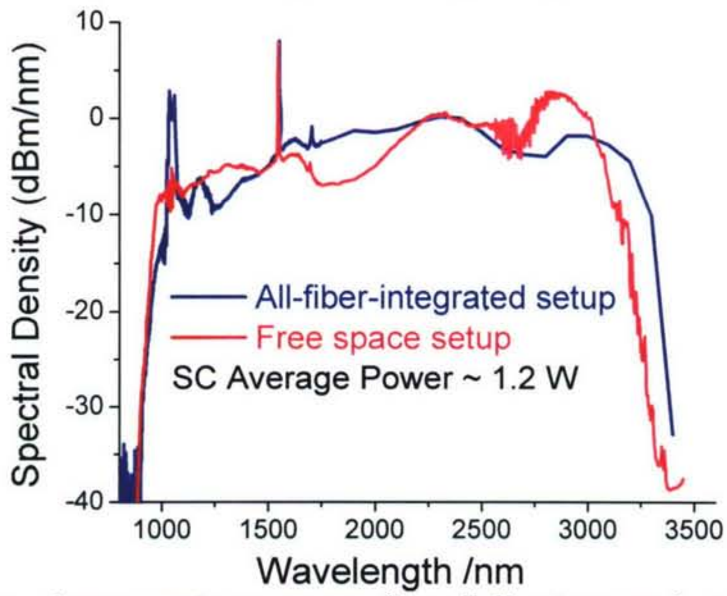

Figure 6. Comparison of super-continuum spectra from all-fiber integrated set-up and table-top, free space set-up.

As an example of the optimization of the system, Figures 7 and 8 show the SC output power versus repetition rate for the pump system. In Figure 7, the total SC time-averaged power is plotted versus repetition rate. As the repetition rate is reduced, the peak power increases in the power amplifier. As the peak power increases, the pump spectrum broadens through self-phase modulation beyond the gain bandwidth of the Er/Yb fiber, so the total output power decreases. After the repetition rate is increased, the SC power flattens because the peak power is reducing, thus limiting the SC generation. Thus, the nonlinearity in the Er/Yb fiber is a limitation as higher peak powers are sought from the pump system.

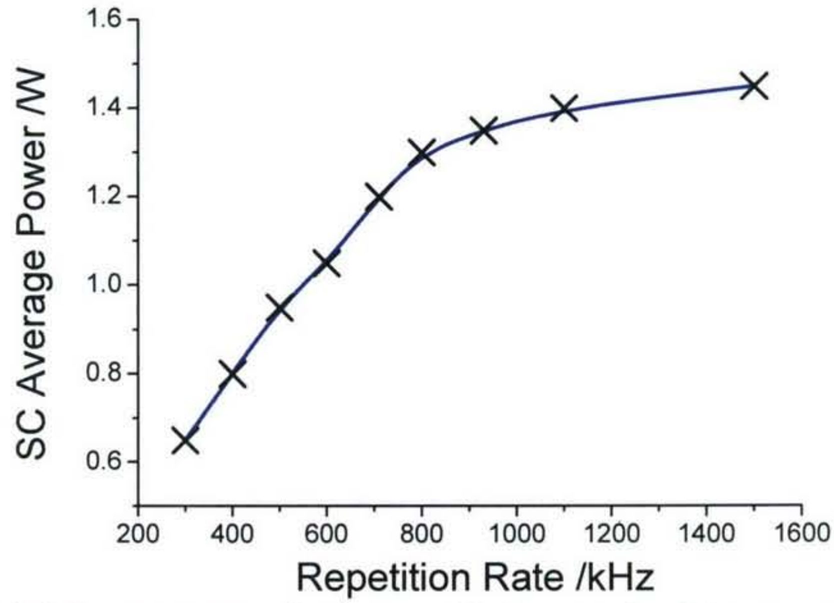

Figure 7. Detailed characterization of high power SC. In particular, SC time averaged power versus pulse repetition rate for the pump laser.

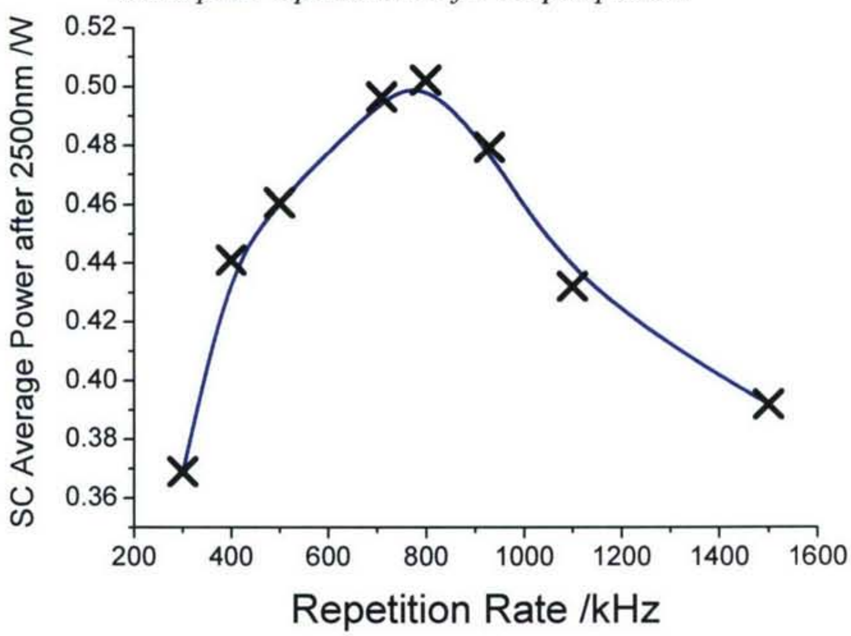

Figure 8. Detailed characterization of high-power SC. In particular, time averaged power for SC beyond 2500nm versus pulse repetition rate for the pump laser.

As another example, Figure 8 plots only the SC time-averaged power in the spectral range beyond 2500nm versus pump repetition rate. For the higher repetition rates, the power decreases because the peak power from the pump laser is decreasing. On the other hand, as the repetition rate is decreased, the peak power increases, but the SC power decreases because more of the spectrum is trying to reach beyond ~3500nm. However, because of the bend induced loss, the SC power is radiated from the fiber. Thus, for a given Er/Yb gain fiber, there is an optimum repetition rate for maximizing the power in the mid-IR SC. We are in discussions with OFS Fitel to obtain larger core size fiber modules, which could permit higher peak powers and increased overall time-averaged outputs. Also, we are obtaining new mid-IR fibers with reduced bend induced loss at the longer wavelengths to extend the wavelength range for the SC.

The project also witnessed a significant increase in the capabilities of the simulations used for model and design the all-fiber integrated systems. The major accomplishment was to refine the simulation code as a design tool for the high power MIRFIL and to obtain good agreement between simulations and experiments. The numerical methods within the code have been refined to increase the running efficiency of the simulator by a factor of two. Then, the validity of the simulation code has been confirmed by matching the parameters and experimental results in both the low and high power experiments. For example, Figure 9 illustrates the comparison of simulation and experiment for the low time-averaged power results, which involve pumping a 3m length of standard single mode fiber followed by 8m of ZBLAN fiber at a peak power of 4kW. Moreover, Figure 10 shows the high power time-averaged results, which involve pumping a 3m length of standard single-mode fiber followed by 11m of ZBLAN fiber at 3kW peak power. In both cases, good qualitative agreement is found, and the deviations at the longer wavelengths are most likely arising from deficiencies in the Raman modeling within the simulation tools. We are looking at upgrading this part of the codes as well. Moreover, the experiments have additional peaks and amplified spontaneous emission near 980nm, arising from the pump to the high power erbium-doped fiber amplifier stage. Since the amplifier pump is not included in the simulation, these features are not found in the simulation results.

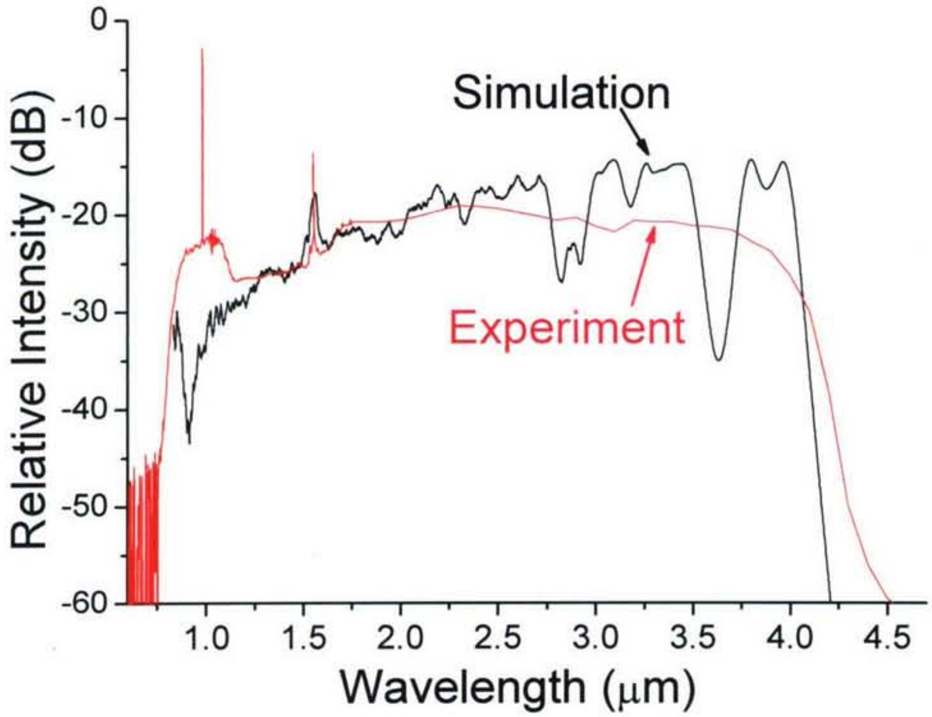

Figure 9. Comparison of simulations and experiments for low power set-up.

The results on the high power experiments and simulation modeling have been published as an Optics Express paper.

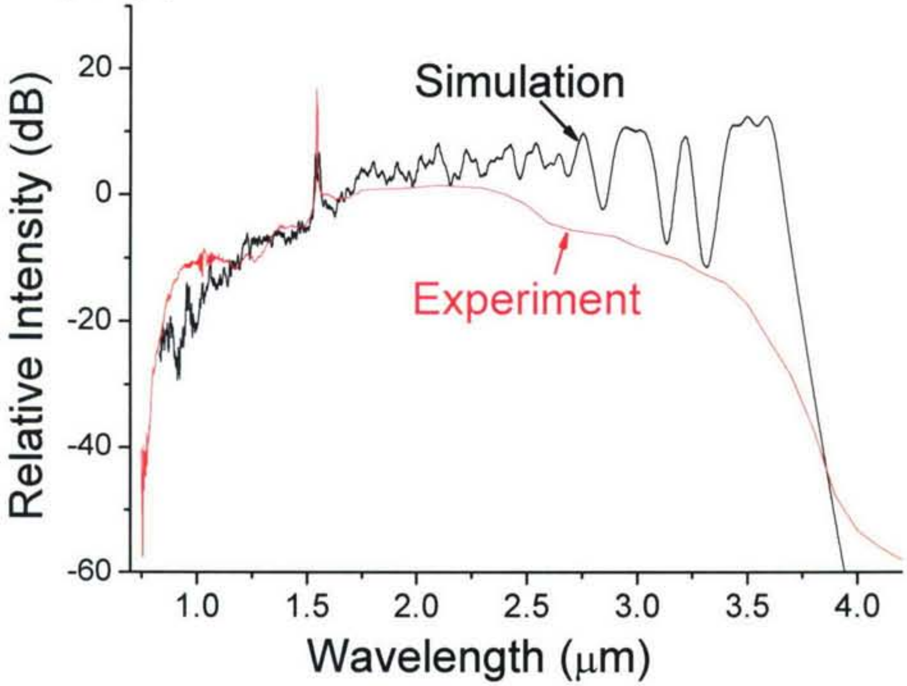

Figure 10. Comparison of simulations and experiments for high power set-up.

In summary, the project was quite successful as it resulted in repeatable demonstrations of the system's ability to generate super-continuum light at power levels of up to 1.3 W of time averaged power. In the Phase II program, the bench-top results will be formed into a product and will be made available to certain system integrators for prototype testing and evaluation.